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HST and VLT observations of Pulsars and their Environments.

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Abstract. The state of the art of optical studies of Isolated Neutron Stars (INSs) and their Pulsar Wind Nebulae (PWNe) is reviewed. In addition, results obtained from recent *HST* and *VLT* observations are presented and discussed.

1. Introduction

The Crab pulsar (PSR B0531+21) was the first isolated neutron star (INS) identified at optical wavelengths (Cocke, Disney, & Taylor 1968). Almost a decade went by till another INS, the Vela pulsar (PSR B0833-45), was detected (Lasker 1976) and confirmed (Wallace et al. 1977). The Vela pulsar, among the faintest objects known at that time ($V \sim 23.6$), was also the last INS detected by photograhic plates. A decade later, came the first CCD detection of the optical counterpart of another INS, Geminga (Bignami et al. 1987). Spurred by this result and by the advent of the new generation telescopes (e.g. the ESO NTT), optical observations of INSs were carried on with revived enthusiasm and at the beginning of the 90s yielded to the detections of the counterparts of PSR B0540-69 (Caraveo et al. 1992), readily confirmed by Shearer et al. (1994), PSR B0656+14 (Caraveo, Bignami, & Mereghetti 1994a) PSR B1509-58 (Caraveo, Mereghetti, & Bignami 1994b), this one later revised by Wagner & Seifert (2000). In the meantime, the identification of Geminga was confirmed through the proper motion measurement of its counterpart (Bignami, Caraveo, & Mereghetti 1993). The launch of *HST* in 1990 increased the chances of detecting new INSs by providing access to the near-UV window through the short-wavelength sensitivity of the Faint Object Camera (FOC). Indeed, soon came the detections of PSR B0950+08, PSR B1929+10 (Pavlov, Stringfellow, & Cordóva 1996) and PSR B1055-52 (Mignani, Caraveo, & Bignami 1997). Likely optical counterparts were also detected for some of the INSs singled out in the ROSAT data (a.k.a. X-ray Dim INSs - XDINSs), namely RXJ 1856-3754 (Walter & Matthews 1997) and RXJ 0720-3125 (Kulkarni & van Kerkwijk 1998). Thus, the number of INSs observed in the optical/UV increased by a factor four in just a decade.

2. The identification status

In recent years, much effort was concentrated on confirming most of the proposed counterparts. Of course, pursuing the identification by searching for optical pulsations at the radio/X-ray period, although ideally the best way, turned out to be extremely difficult due to the intrinsic object faintness. Furthermore, almost none of the middle-size/large ground-based telescopes offered devices for high-resolution timing and very few of them were easily adaptable to suited guest instruments. Such problems prompted observes to devise alternative identification strategies. The use of proper motion measurements of the candidate counterpart, successfully experimented in the case of Geminga (Bignami et al. 1993), proved to be a powerful tool. Indeed, proper motion yielded the confirmation of the optical counterparts of PSR B0656+14 (Mignani, De Luca & Caraveo 2000), although a marginal detection of optical pulsations did exhist (Shearer et al. 1998), of RXJ 1856-3754 (Walter 2001), of PSR B1929+10 (Mignani et al. 2002) and of RXJ 0720-3125 (Motch, Zavlin, & Haberl 2003), all but the last one achieved through high-resolution *HST* imaging. In the meantime, the Space Telescope Imaging Spectrometer (STIS) on *HST*, equipped with a UV-sensitive MAMA device, took up the pathfinder task of the dismissed FOC. In addition, with a timing resolution of 125 μs, the STIS made it possible to perform timing observations of pulsars in this spectral region. Apart from the Crab pulsar (Gull et al., these proceedings), four other pulsars have been observed to date by the STIS. While the timing of PSR B1929+10 has not provided so far conclusive results (Mignani, p.c.), pulsations at the known period have been clearly detected from the Vela pulsar and Geminga (Romani & Pavlov 2003) as well as from PSR B0656+14 (Gull et al., these proceedings). While for the Vela pulsar the STIS data have provided the first measure of its light curve in the UV, for PSR B0656+14 and Geminga detected pulsations provided further confirmation of the identifications, improving on the earlier timing results of Shearer et al. (1997) and Shearer et al. (1998). By exploiting the high positional accuracy provided by *Chandra*, likely candidate optical counterparts have been also detected by the STIS for two newly discovered XDINSs, RXJ 1308.6+2127 and RXJ 1605.3+3249 (Kaplan, Kulkani, & van Kerkwijk 2002,2003). The last entry is PSR J0437-4715, the first ms-pulsar detected at optical/UV wavelengths, recently detected with the STIS (Kargaltzev, Pavlov, & Romani 2003). Table 1 summarizes the current (October 2003) optical/UV identification status of INSs. As it is seen, owing to their intrinsic faintness, most INSs have been detected only thanks to their proximity and small interstellar absorption. Only the Crab pulsar, PSR B1509-58 and PSR B0540-69 have been detected at more than 1 kpc distance. Looking at Table 1 we see that thanks to the new telescopes/CCD technologies, the INS discovery rate increased from *one per decade* to almost *one per year*. In particular, we note how the *HST* contribution has been fundamental, providing nearly all of the INS detections obtained in the last 10 years i.e. half of the total. As a matter of fact, so far *HST* has clearly detected all the INSs it was targetted to. Instead, the *VLT* potentialities have been only partially exploited in the identification work, yielding so far only to one detection. Finally, proper motion measurements, although requiring much longer time spans, turned out to be as efficient as timing in securing optical identifications of INSs.

Name	*Proposed*	*Confirmed*	*Evidence*	*mag*	*d(kpc)*	A_V
Crab	1968	1969	TIM	16.6	1.73	1.6
Vela	1976	1977	TIM	23.6	0.23	0.2
Geminga	1987	1993/1998,*2003*	PM/TIM	25.5	0.16	0.07
B0540-69	1992	1994	TIM	22	49.4	0.6
B0656+14	1994	1997,*2003*/*2000*	TIM/PM	25	0.29	0.09
B0950+08	*1996*			27.1	0.26	0.03
B1929+10	*1996*	*2002*	PM	25.6	0.33	0.15
B1055-52	*1997*			24.9	0.72	0.22
RXJ1856-3754	*1997*	*2001*	PM	25.7	0.14	0.12
J0720-3125	1998	2003	PM	26.7		0.10
B1509-58	**2000**			25.7	4.18	5.2
RXJ1308.6+2127	*2002*			28.6		0.14
RXJ1605.3+3249	*2003*			26.8		0.06
J0437-4715	*2003*				0.14	0.11

Table 1. INSs identification status. The first four columns give the name, the publication year of the counterpart discovery and of its unambigous confirmation (italics= *HST*, bold=*VLT*) and the identification evidence, i.e., either pulsations (TIM) or proper motion (PM). Columns five to seven give the V-band magnitude when available (see Table 2), the distance in kpc, either obtained from the DM or from radio/optical parallaxes (see $http : //rsd - www.nrl.navy.mil/7213/lazio/ne\_model/$), and the interstellar absorption A_V, as measured directly or from the N_H derived from the soft X-rays spectral fits.

3. New HST and VLT observations of INSs: The chase goes on

Spurred by recent results, the search for new optical counterparts of INSs has been pursued both with the *HST* and the *VLT*. After the first-light investigation of PSR B1706-44 (Mignani, Caraveo, & Bignami 1999), the *VLT* observed a number of pulsars and INS candidates, although with not much luck so far.
One of the obvious targets was the $\sim$ 1.7 Myrs old, nearby ($\sim$ 200 pc) PSR J0108-1431. Although no potential counterpart was found at the revised radio position (Mignani, Manchester, & Pavlov 2003), the derived upper limits ($V \simeq 28$, $B \simeq 28.6$, $U \simeq 26.4$) allowed to constrain the surface temperature of the neutron star to $T < 8.8\ 10^4$ K (for d=200 pc and $R = 13$ km), a value in line with the expectations of standard cooling models for such an old INS (Mignani et al. 2003a). The *VLT* also observed for the first time ms-pulsars, all selected according to their $\dot{E} \approx 10^{33}$ ergs s^{-1}, X-ray emission, close distance ($<$ 500 pc) and low interstellar absorption. No counterpart was identified for PSR J2124$-$3358 ($U \geq 26$, $B \geq 27.7$ and $V \geq 27.8$; Mignani & Becker 2003) and PSR J0030+0451 ($B \geq 27.3$, $V \geq 27$ and $R \geq 27$; Koptsevich et al. 2003), two ms-pulsars very similar in both their timing and X-ray emission. For PSR J0030+0451 (Koptsevich et al. 2003), and likely also for PSR J2124-3358 (Becker & Mignani 2003), the optical flux upper limits are well below the extrapolation of the non-thermal *XMM* X-ray spectrum. In case of non-thermal optical emission, this would imply a turnover in the optical/X-ray spectrum. The derived neutron star surface temperatures (13 km radius) for PSR J2124-3358 (Mignani

& Becker 2003) and PSR J0030+0451 (Becker et al. 2003) are $\leq 4.5\ 10^5$ K and $\leq 9\ 10^5$ K, which are above the value measured for PSR J0437-4715 (Kargaltzev et al. 2003). Unconclusive results were reported from shallower observations of PSR J1024−0719 and PSR J1744−1134 (Sutaria et al. 2003) for which no spectral X-ray data are available for comparison. The *VLT* observed also the 424 ms pulsar 1E 1207−5209 in the young ($\sim$ 7,000 years) SNR G296.5+10.0 but it failed to detect any object brighter than R$\sim$27.1 and V$\sim$27.3 within the $\sim$ 2 arcsec, boresight-corrected, *XMM* error circle thus making this apparently young object more similar to middle-aged INSs (see also De Luca et al. 2003, De Luca et al. these proceedings). The 16 ms X-ray pulsar PSR J0537-6910 has been recently observed with the *HST*, taking advantage of the revised and more precise ($\leq$ 1 arcsec) *Chandra* position (Wang et al. 2001). Thanks to the spatial resolution and sensitivity of the recently installed Advanced Camera for Survey (ACS) it was possible to improve on the ground-based results of Mignani et al. (2000) and resolve faint stellar sources in the crowded core of the N157B SNR. Multicolor imaging has pinpointed few, new, potential counterparts characterized by unusual colours (Mignani et al. 2003b) which are being investigated through timing analysis with the *HST*/STIS. Finally, recent *HST* and *VLT* observations have contributed in clarifying the nature of the puzzling Compact Central Object (CCO) 1E 161348-5051 in the young ($\sim$ 2,000 years) SNR RCW103. Originally considered as a "good" INS candidate, its real nature has been debated after the discovery of long term variations, $\sim$ 6 hours periodicity and dips of the X-ray flux (see Becker & Aschenbach and references therein). Deep IR observations with the *VLT* have detected a potential counterpart ($J = 22.3$,$H = 19.6$,$K = 18.5$) which has been confirmed by a follow-up with the *HST*. Searches for correlated long timescales IR/X-ray variability with *Chandra* (PI G. Garmire) as well as for a 6 hrs IR periodicity have been unconclusive so far (Sanwal et al. 2003). If the object is indeed associated with the CCO, at the source distance it could only be a low-mass star or a fossil disk. It could thus be the first case of a LMXB identified at the center of a SNR.

4. Optical emission properties of INSs

The spectral database and the derived spectral properties for the INSs in Table 1 are summarized in Table 2. As it is seen, only in six cases (Crab, B0540-69, Vela, Geminga, J0437-4715 and RXJ 1856-3754) the knowledge of the spectrum can rely on optical/UV spectroscopy. Indeed, it is basically thanks to the advent of the 10m class telescopes, like the Keck and the *VLT*, that spectroscopy of the faintest INSs became possible. For most INSs, multicolor photometry is still the only source of spectral information. Only for four INSs (Crab, Vela, B0656+14 and Geminga) the spectral coverage spans all the way from the IR to the UV. For all of them, with the exception the Crab, IR detections were provided for the first time by the *HST* and the *VLT* . This was crucial to unveil the presence of both thermal and non-thermal spectral components, whose contributions are expected to be markedly different in the IR and in the UV. For five INSs (B1509-58, B1055-52, B1929+10, RXJ 1605.3+3249 and RXJ 1308.6+2127) only one, two passband photometry is available and the characterization of the optical spectrum is only tentative.

Name	*Log* τ	*Spec.*	*Phot.*	α	T	*Comments*
Crab[1]	3.1	1100-9000	UV,UBVRI,JHK	-0.11	-	$PL_o < PL_x$
1509-58[2]	3.19		R			
0540-69[3]	3.22	2500-5500	UBVRI	+0.2	-	$PL_o < PL_x$
Vela[4]	4.05	4500-8600	UV,UBVRI,JH	+0.12	-	$PL_o \sim PL_x$
0656+14[5]	5.05		UV,UBVRI,JHK	+0.45	8.5	$PL_o \sim PL_x$ $BB_o \sim BB_x$
Geminga[5]	5.53	3700-8000	UV,UBVRI,JH	0.8	4.5	$PL_o < PL_x$ $BB_o \sim BB_x$
1055-52[6]	5.73		U			
J0720-3125[7]	6.4		UV,UBVR	-1.4	4*	$BB_o > BB_x$
1929+10[8]	6.49		UV,U	+0.5	-	$PL_o < PL_x$
0950+08[9]	7.24		U,BVI	+0.65	-	$PL_o \sim PL_x$
0437-4715[10]	9.2	1150-1700		-	1.0	$BB_o > BB_x$
J1856-3754[11]	?	3600-9000	UV,UBV	-	2.3	$BB_o > BB_x$
J1605.3+3249[12]	?		VR			
J1308.6+2127[13]	?		V			

* a distance of 300 pc is assumed

[1]Sollerman et al. (2000); [2]Wagner & Seifert (2000); [3]Nasuti et al. (1997); [4]Shibanov et al. (2003); [5]Komarova et al. (2003); [6]Mignani et al. (1997); [7]Motch et al. (2003); [8]Mignani et al. (2002); [9]Zharikov et al. (2003); [10]Kargaltzev et al. (2003); [11]van Kerkwijk & Kulkarni (2001); [12]Kaplan et al. (2003); [13]Kaplan et al. (2002)

Table 2. Spectral database for the INSs in Table 1, sorted according to their spin down age τ (column two) and grouped by age decades. Column three and four give the spectral range (in Å) covered by spectroscopy and by photometry (band-coded). The spectral index α and temperature (in units of $10^5 K$) of the observed power-law ($F_\nu \sim \nu^{-\alpha}$ and blackbody components (hyphens stand for non-detections) are listed in columns five and six, respectively. The last column tells wether the flux of the PL/BB optical (PL_o;BB_o) components is higher (>), lower (<) or comparable ($\sim$) to the optical extrapolation of the analogous X-rays components (PL_x;BB_x).

Although the spectral database is far from being complete, some general patterns can be recognized in Table 2. First of all, the spectrum grows in complexity as a function of the INSs age, passing from a single power-law (PL) to a composite one featuring both PL and blackbody (BB) components. The underlying presence of a PL component is also recognizable from the correlation between the optical luminosity L_o and the rotational energy loss $\dot{E}$ (see Kramer, these proceedings). Although in some cases the optical PL/BB components do match the extrapolation of the analogous components observed in the X-ray domain, no general optical/X-ray correlation can be recognized. Thus, optical and X-ray emission mechanisms are not always related to each other. The optical emission properties of INSs can be summarized as follows for the different age class indentified in Table 2:

(i) Young INSs: They are characterized by single PL spectra, all with spectral index $\alpha_\nu > 0$ apart from the Crab which shows evidence for a spectral turnover in the optical/IR (Sollerman et al. 2000).

(ii) Middle-aged INSs: They feature composite spectra with both PL and BB components, the former dominating in the IR, the latter in the UV. In general they have spectral indexes $\alpha_\nu > 0$ which, at least for PSR B0656+14, seem to be steeper than in Young INSs. For both PSR B0656+14 and Geminga, the optical BB is consistent with the extrapolation of the X-ray one and is likely produced from the whole neutron star surface. For PSR B1055-52 nothing can be said but that the U-band flux is consistent with the extrapolation of the X-ray PL.
(iii) Old INSs: Both PSR B1929+10 and PSR B0950+08 feature single PL spectra with spectral indexes $\alpha_\nu > 0$ and steeper than those of Middle-aged INSs. An additional BB component might be present but it can not constrained by the present data.
(iv) ms-pulsars: The UV spectrum of PSR J0437-4715 is a BB, with a temperature higher than the one of the > 20 times younger PSR J0108-1431. For PSR J2124-3358 and PSR J0030+04651 (see §3), the available flux upper limits seem also to suggest a BB spectrum.
(v) XDINSs: For RXJ 1857-3754 the spectrum is a BB and it is above the optical extrapolation of the X-ray one. On the other hand, the spectrum of RXJ 0720-3125 seems to be composite, with a dominant BB component (also above the optical extrapolation of the X-ray one) and a PL with $\alpha_\nu < 0$.

5. HST observations of Pulsar Wind Nebulae

Although a few Pulsar Wind Nebulae (PWNe) have been detected in X-rays by *Chandra* (Gaensler et al., these proceedings), optical observations are still limited to a few cases. Apart from the Crab (e.g., Hester et al. 2002), *HST* has observed only three other young pulsars with PWNe.
The structure of the PSR B0540-69 PWN has been resolved by the *Chandra*/HRC (Gotthelf & Wang 2000) in three different components: a point-like source coincident with the pulsar, an elongated toroidal structure around it and a jet-like feature apparently protruding from the pulsar. In the optical, a PWNe is clearly detected in the *HST* data of Caraveo et al. (2000) with a very similar elongated pattern and a shallow maximum southwest of the pulsar. Also the faint jet, marginally visible in the *Chandra* image, does have an optical counterpart.
The Vela PWN features a brighter inner part ($\approx 2'$), with two arcs, a jet, and a counter-jet, symmetrical around the pulsar's proper motion direction. The inner PWN is then embedded into an extended emission (outer PWN), surrounded by a bean-shaped diffuse nebula ($\sim 2' \times 2'$) with an elongated region of fainter emission and a 100$''$-long outer jet southwest and northwest of it, respectively (see also Kalgartzev et al. these proceedings). To investigate the reality of the previously claimed optical PWN (Ögelman et al. 1989), Mignani et al. (2003c) have compared *Chandra* and very deep *HST* images of the field but no optical counterparts of the known X-ray features could be identified with 3σ (extinction corrected) upper limits of ≈ 27.9 mag arcsec^{-2} and ≈ 28.3–27.8 mag arcsec^{-2} on the brightness of the inner and outer PWN, respectively. By using wider ESO *NTT* and 2.2m images, Mignani et al. (2003c) also set upper limits of ≈ 27.1 mag arcsec^{-2} on the optical emission from the southwest extension of the X-ray nebula. While the derived upper limits for the inner/outer PWN are

not far from the extrapolation of the available X-ray/radio data, the ones for the southwest extension are at least 3 orders of magnitudes above the expected value. For the PSR J0537-6910 PWN no conclusive results have been obtained so far. A preliminar search for an optical PWN was performed by Wang et al. (2001) using archived *HST* observations but they were too shallow to set stringent constraints. Their results can now be improved thanks to recent, much deeper, *HST*/ACS observations of the field (Mignani et al. 2004).

6. Conclusions

INSs with either a secured or a likely optical counterpart amounts now to 14, i.e., a number comparable to those detected in X-rays in the pre-ROSAT era. Thus, the optical branch, originally confined to a handful of representative cases, is growing in importance occupying a larger and larger niche in the multiwavelength studies of INSs. Certainly, much work remains to be done to reduce the gap, both in terms of quality and quantity, with the X-ray domain. More deep imaging observations are needed to pinpoint new candidates, to study correlations between the emission properties (luminosities, spectra) as a function of the pulsars' parameters and to search for diffuse emission structures (PWNe and bow-shocks). More timing observations are required, both to secure faster identifications and to provide a broader characterization of the pulsars' lightcurves. Finally, more spectroscopy is critical to better define the emission processes. These are tasks both for the current 10 m class telescopes and for the next generation of extra-large telescopes (Becker & Mignani, these proceedings).

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